The Building up and Evolution of Galactic Disks

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Abstract. The formation and evolution of disk galaxies in the cosmological context is studied. We consider the observable properties of disk galaxies and treat the disk formation and galactic evolutionary processes in a self-consistent fashion. We find the matter accretion regime to be the dominant ingredient in establishing the Hubble sequence. The accretion regime is a phenomenon directly related to the statistical properties of the primordial density fluctuations from which disk galaxies emerged.

1. Introduction

Disk galaxies exhibit well defined observational properties and correlations, many of which are on the basis of the Hubble sequence (HS). The origin of such sequence is an outstanding problem of astrophysics. There are two directions in which this problem has been studied: considering the HS as a result of primordial initial conditions or (and) of secular disk evolution. Since galaxies are not only individual "ecosystems" where stars are born, live, and die, but also the structural unities of the universe as a whole, the origin of at least some of their physical properties should be related to the cosmological initial conditions. Only through a combined study, where the evolutionary processes of the visible galactic system as well the cosmological initial conditions are taken into account, it will be possible to distill the main ingredients that establish the HS. This is the line we follow in order to construct a scenario of galaxy formation and evolution mainly focused to disk galaxies.

1.1. Gas accretion in disk galaxies

The relevance of gas accretion on the evolution of galactic disks has been pointed out repeatedly. Discrepancies between observations and the simple "closed-box" evolutionary models like the G-dwarf problem, the fast gas consumption, the gas depletion paradox, and the systematic variation of the star formation (SF) timescale along the HS, can be solved stating that disk did not form instantaneously but have grown by a gradual process of accretion, which is fast at the initial epochs for early type disks and slower for late-type disks.

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Likewise, evolutionary models where the SF, hydrodynamics, and gravitational interactions (including dark matter) of a galactic disk are treated in a self-consistent fashion (Firmani *et al*. 1996a, FHG, see also Firmani & Tutukov 1992, 1994) have shown that late-type disks can not be obtained without gas accretion.

1.2. Gravitational collapse of primordial fluctuations

In the frame of the most predictive inflationary cosmological models, where baryon matter is only a small fraction of cold dark matter, cosmic structure develops by a process of continuous merging and accretion. Because galactic disks are cold and thin structures they could not have suffered major mergers (Tóth & Ostriker 1991). On the other hand disk galaxies are typically located in low density environments where mayor mergers are rather rare. That is why we envisage disk galaxy formation as the process of gravitational collapse of individual density profiles around the local maxima of the fluctuation field; of course some substructure (merging) will be present, but we treat it as a second-order ingredient.

The possible mass growth histories of a given present-day galaxy can roughly be estimated through a particular physical interpretation of the conditional probabilities found by Bower 1991, Bond *et al*. 1991, and Lacey & Cole 1993. We calculate the virialization of dark halos following these histories or accretion regimes assuming spherical symmetry (see Avila-Reese & Firmani 1996, AF). Galactic disks are built up into the dark halos assuming detailed conservation of angular momentum distribution. The evolution of accreting disks is followed through a previously developed numerical code (FHG). In this way, we explore how do the different cosmological accretion regimes influence the evolution of galactic disks devoting special attention to disk structure, SF history, Hubble type, rotation curve and the Tully-Fisher relation.

2. Initial conditions and formation and evolution of galactic disks

We are interested in studying the gas mass and angular momentum accretion regimes over the galactic disks. As was mentioned above, our main assumption is that these regimes are related to the cosmological collapse of primordial density fluctuations. For Gaussian random fields, it is possible to statistically derive mass growth histories. We use the Monte Carlo formalism as in Lacey & Cole and for a given mass we found the average trajectory and the two still statistically sifnificant average deviations from the most possible case (AF). Since the mass growth histories are fixed to the present-day mass, these trajectories reflect the range and distribution of possible accretion regimes of disk galaxies (see fig. 1 of AF). The regimes are characterized by the parameter $\gamma(t) \equiv \frac{d\ln M(t)}{d\ln t}$ which is measured from today back to the past. For every mass one has a low, average, and high accretion regimes which slowly change with the mass (AF).

The virialized structures which arise according to these accretion regimes are calculated using an extension of the secondary infall mechanism (see AF). The formation of disks in the dark halos implies gas energy dissipation and

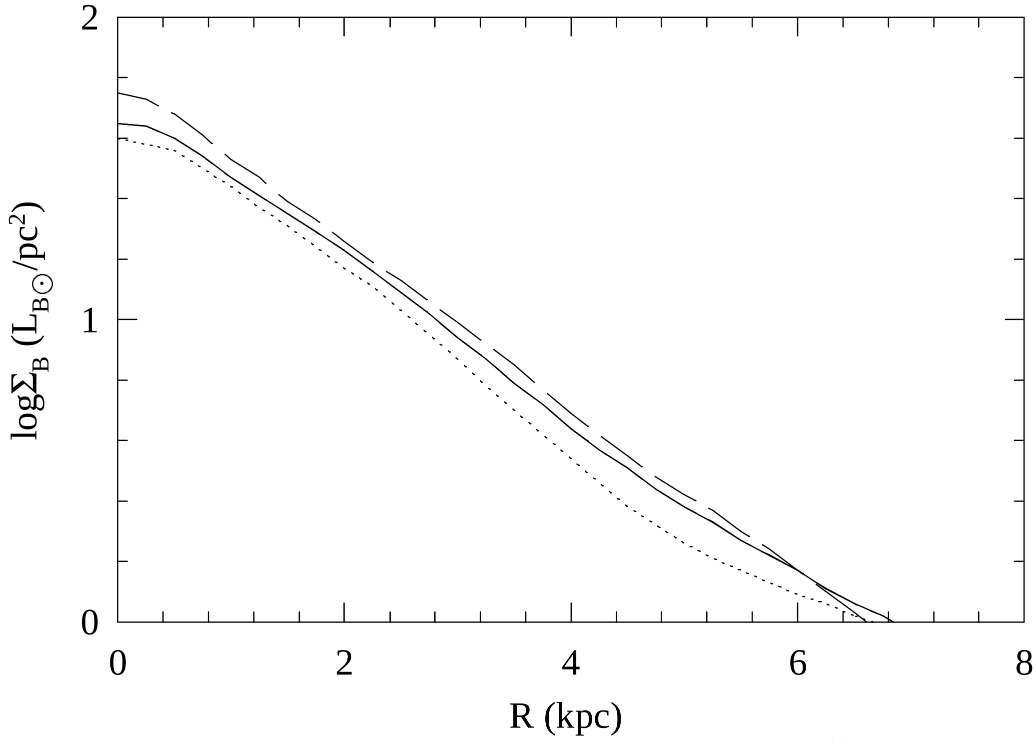

Figure 1. The B radial surface brightness profiles of a $10^{11} M_\odot$ galaxy. Dashed, solid, and dotted lines correspond to the low, average and high accretion regimes, respectively

some initial angular momentum. We do not treat the gas cooling and assume that as soon as a shell virializes, the baryon mass fraction cools and falls to the center in a dynamical time. The disk is built up with the infalling gas from the evolving dark halo. Concerning the angular momentum, it is widely accepted that galaxies acquire it in the linear regime through the tidal torques due to the neighboring density fluctuations. Because in our approximation the halos are spherically symmetric (the moment of inertia vanishes) we can not calculate the value of the angular momentum. However, using the Zel'dovich approximation it is possible to calculate the dependence of the acquired angular momentum on the distance from the center of the collapsing region. A simple extension of a spetial formalism (e.g. see White 1994) was applied in order to obtain this relation, and the value of the tidal torque (a free parameter) was fixed through a normalization to the Galaxy. It is encouraging that the spin parameter λ predicted in numerical simulations is in agreement with such a normalization.

Under the assumption of detailed angular momentum conservation, the gas falls just to the radius where its angular momentum provides centrifugal support, resulting in a disk mass distribution which tends to be exponential (e.g. Gunn 1981, 1987). We tested the robustness of the result introducing several departures from this approach where the total angular momentum was conserved but some radial transfer of the falling gas was allowed. An exponential disk was ever the result of this gradual collapse.

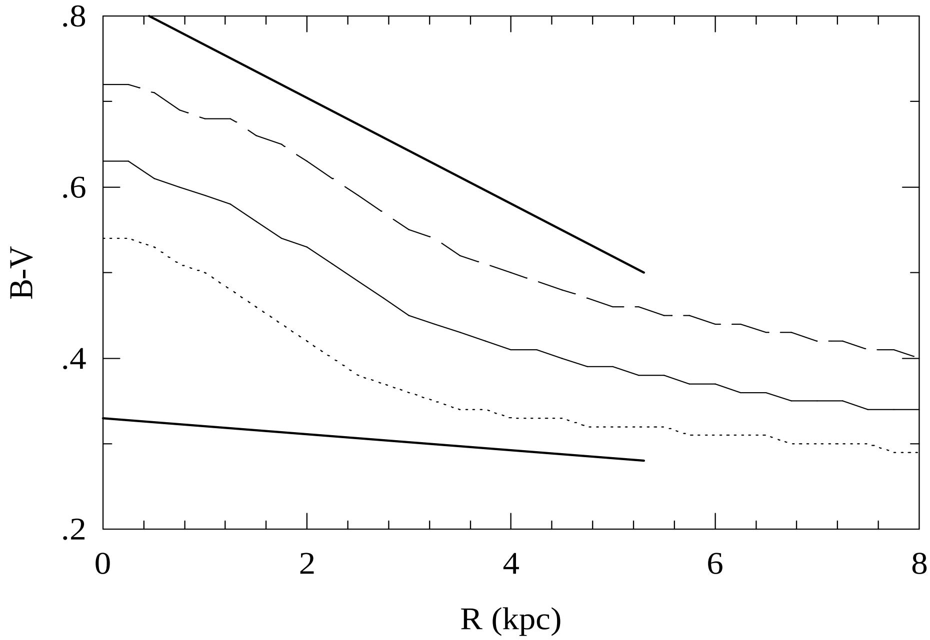

Figure 2. Radial B-V color profiles for a $10^{11} M_{\odot}$ galaxy.The line simbols are the same as in fig.1. For explanations regarding the two extreme solid lines see the text

In the forming disks, galactic evolutionary processes will arise. SF, energy injection to the ISM, turbulent dissipation, self-gravity and gravitational instabilities, and their non-linear interactions are some of the crucial ingredients which regulate the evolution of galactic disks. A theoretical approach where SF is driven by gravitational instabilities and regulated by energy balance between SN input and turbulent dissipation is applied (FHG). Gravity produced by the forming disk and dark halo and the corresponding interaction between them is treated in detail. In the cases of slowly growing disks, after some short timescales, the SF rate becomes proportional to the gas accretion rate, while disks formed by a fast collapse, where the gas is supplied only by the mass loss from stars, will have a declining SF rate with time

3. Results

Using the approach described above and in AF we present here some preliminary results on disk formation and evolution in the cosmological context where *a priori* some key ingredients related to the initial conditions, the evolutionary processes, and the observational properties (HS) where remarked and self-consistently combined in order to construct a scenario which we hope will help us to better understand the real phenomenon.

Our calculations are made here for a standard cold dark matter model, and the results are shown for a $10^{11} M_{\odot}$ galaxy.

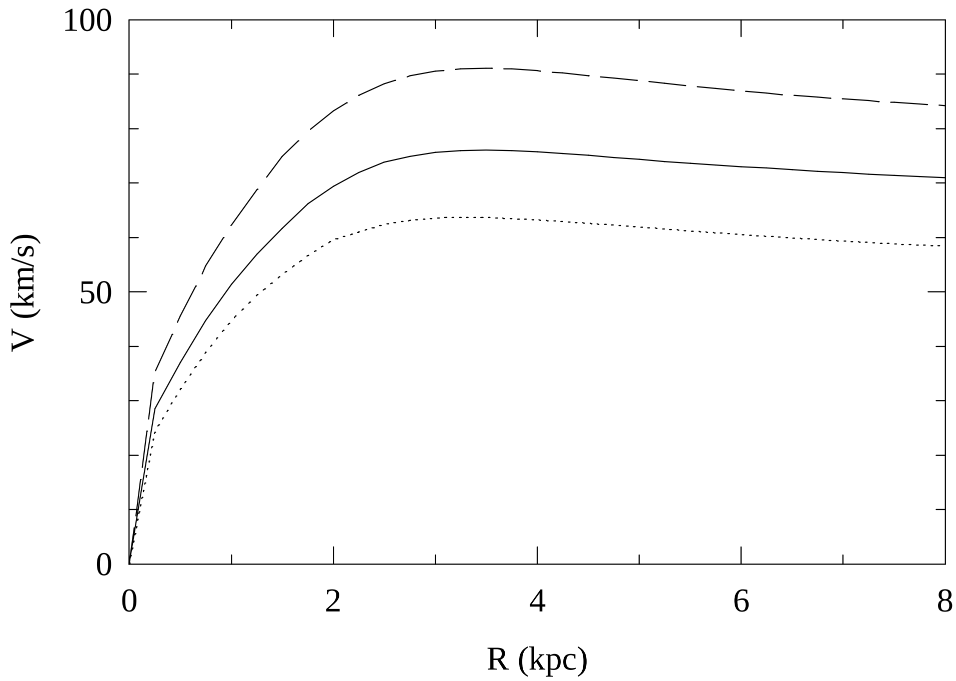

Figure 3. Rotation curves for a $10^{11} M_{\odot}$ galaxy. The line simbols are the same as in figure 1

Figure 1 shows the exponential behavior of the surface brightness for the three average mass growth histories. Concerning the SF history the models predict gentle radial gradients in the $B-V$ colors (figure 2) in agreement with recent observations (de Jong 1995). The average colors of the disk change with the accretion regime going from $B-V \approx 0.4$ for high accretion regimes to $B-V \approx 0.7$ for low accretion regimes. The angular momentum transfer from the infalling gas to the dark halo may influence the blue limit, while the red limit is fixed basically by our library of red giant evolutionary tracks. The extreme cases of a sudden initial SF burst and a constant SF history on the Hubble time are shown in Figure 2 with thick solid lines.

In Figure 3 the final rotation curves are presented. They retain some information about the primordial fluctuations notwithstanding the fact that the contraction of baryon matter has altered the gravitational potential in the visible galactic regions. It is clearly seen that galaxies formed by a fast collapse are more concentrated than those emerged from an extended collapse.

The gravitational contribution of dark matter in the center appears to be sensible to the initial kinetic energy content (see also AF). In order to be in agreement with published decompositions of rotation curves we have to fix a high kinetic energy content.

The results of our models are in agreement with the Tully-Fisher relation (figure 4) providing evidence about its cosmological origin.

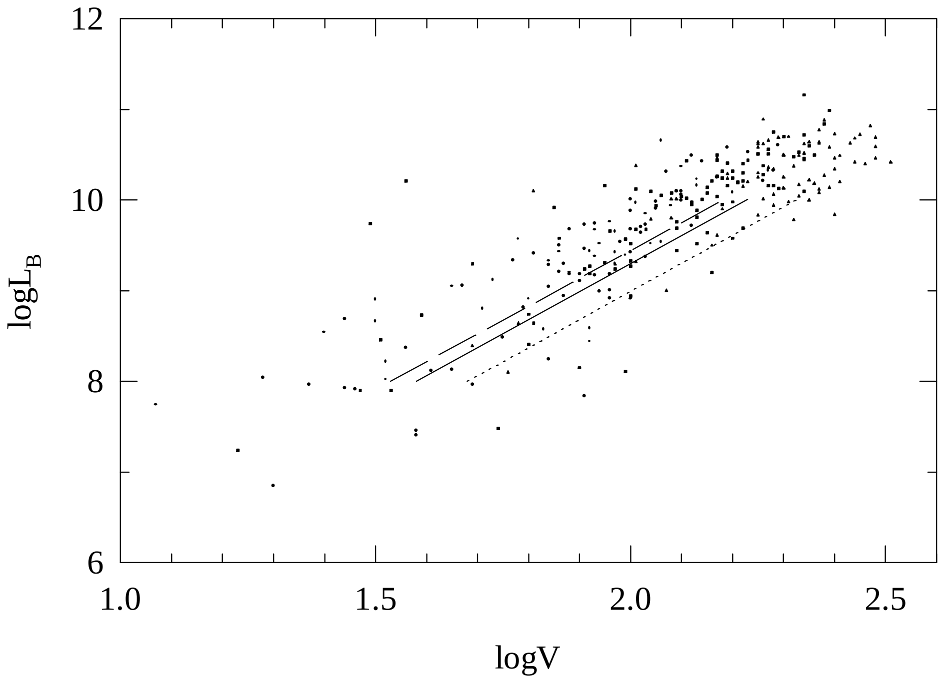

Figure 4. The Tully-Fisher relation in B-luminosty for a sequence of models corresponding to the high (dashed line), average (solid line), and low (dotted line) accretion regimes. The points are the observational data estimated from a compilation of the RC3 and Tully catalogs (see Firmani & Tutukov 1994). The velocity is not that which was obtained from direct observations, and the points only approximately reflect the Tully-Fisher relation

4. Conclusions

In the scenario for disk galaxy formation and evolution proposed here, galaxies arise from the gravitational collapse of density profiles around local maxima of the primordial density field in an expanding universe. The role of substructure (merging) is considered as a second-order phenomenon. The initial conditions generated in agreement with this vision were used in galactic evolutionary models which finally predicted present-day galactic disks with exponential blue luminosity profiles, color radial gradients, near flat rotation curves, and a Tully-Fisher relation in blue with a slope of ~ 3.3. The calculated properties that can define the HS are the integral $B-V$ color, the SF history, the present gas content, and the degree of compactness of the galaxies. All these properties have shown to follow a sequence along the range of cosmological accretion regimes suggesting that this could be the dominant ingredient in establishing the HS. Although we have not yet made detailed calculations it is easy to identife the control of the accretion regime also on the old stellar spheroid component which can be formed at the beginning of the evolution by a violent collapse (Firmani *et al.* 1996b).

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